BASIC RESEARCH ON SEISMIC AND INFRASONIC MONITORING OF THE EUROPEAN ARCTIC

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NORSAR

Sponsored by Army Space and Missile Defense Command

Contract No. W9113M-05-C-0224

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ABSTRACT

This project represents a three-year research effort aimed at improving seismic and infrasonic monitoring tools at regional distances, with emphasis on the European Arctic region, which includes the former Novaya Zemlya test site. The project has three main components: a) to improve seismic processing in this region using the regional seismic arrays installed in northern Europe, b) to investigate the potential of using combined seismic/infrasonic processing to characterize events in this region and c) to carry out experimental operation, evaluation and tuning of the seismic threshold monitoring technique.

The recent upgrade of the Spitsbergen seismic array, which has included the installation of five new three-component seismometers, as well as an increase in the sampling rate from 40 to 80 Hz, has resulted in significant improvements in high-frequency signal characterization as well as S-phase detection. Our studies have shown a remarkably efficient wave propagation from events near Novaya Zemlya across the Barents Sea. Significant signal energy at frequencies of up to 30 Hz and above has been observed, even for seismic events below a magnitude 3 at an epicentral distance of more than 1,000 km. In order to investigate if this same efficient propagation could be observed at the ARCES array in northern Norway, we have recently installed additional recording equipment at the center broadband element of ARCES, with a sampling rate of 100 Hz. Our initial results are similar to those seen at Spitsbergen. We should note that the available high-frequency data so far does not include events to the east and northeast of the ARCES array, and the high-frequency propagation from the Novaya Zemlya region to ARCES is therefore still unknown. As more data are accumulated, we may be in a position to carry out a detailed study of the high-frequency propagation characteristics for additional paths in the region. Analysis of data from temporary seismic stations installed as part of the ongoing International Polar Year is expected to provide an important contribution to such a study.

We have continued our infrasonic studies, applying the data from the current array network in northern Europe. As a special case study, we have analyzed recorded infrasound signals from four confirmed rocket launches at the Plesetsk Cosmodrome in northwest Russia as well as infrasound signals from five possible (unconfirmed) launches from the same site. We have in particular attempted to obtain an understanding of the overall signal characteristics as well as the inherent variability among these signals. We have used available recordings both from the Apatity infrasound array and from the stations of the Swedish Infrasound Network. For two of the confirmed launches, we have sufficiently good quality recordings from three arrays (Apatity at a distance of 628 km, Kiruna and Jämtön, each at a distance of about 1,000 km). The backazimuths estimated during the wavetrains show some significant variations, with a deviation from the theoretical values by up to about 10 degrees. Particularly interesting is the azimuthal pattern at the Apatity array, which shows a clear trend of changing backazimuths with time, thus giving indications of a moving source. For the remaining two confirmed launches, we have only recordings from one array (Apatity), and again we see a time-varying trend, but in one of the cases the direction of change is reversed. This may be explained by differences in rocket takeoff directions relative to the Apatity station.

For the five unconfirmed events (which all occurred during one day: 23 January 2007) we see signal characteristics that are generally consistent with the observations of the confirmed launches, and it seems likely that they correspond to actual (unconfirmed) Plesetsk launches. We have calculated differential travel-times for onsets of the infrasound signals at the Jämtön and Kiruna stations relative to Apatity. The onsets were read visually from vespagrams and had a rather high uncertainty. We find that we cannot separate the source location for the unknown signals from the verified Plesetsk launches based on these differential travel times, and we therefore consider it likely that they could be rocket launches from this site.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Basic Research on Seismic and Infrasonic Monitoring of the European Arctic**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NORSAR,PO Box 53,N-2027 Kjeller Norway,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

Proceedings of the 30th Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies, 23-25 Sep 2008, Portsmouth, VA sponsored by the National Nuclear Security Administration (NNSA) and the Air Force Research Laboratory (AFRL)

14. ABSTRACT

see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVES

The objective of the project is to carry out research to improve the current capabilities for monitoring small seismic events in the European Arctic, which includes the former Russian test site at Novaya Zemlya. The project has three main components: a) to improve seismic processing in this region using the regional seismic arrays installed in northern Europe, b) to investigate the potential of using combined seismic/infrasonic processing to characterize events in this region, and c) to carry out experimental operation, evaluation and tuning of the seismic threshold monitoring technique, with application to various regions of monitoring interest.

RESEARCH ACCOMPLISHED

Study of High-Frequency ARCES Recordings

We have carried out an initial investigation of recordings of high-frequency seismic waves at the ARCES array. This contribution describes initial results from these studies. We have analyzed in detail a number of seismic events at regional distances from ARCES, with epicentral distances ranging from 270 to about 1,300 km, and assessed the amount of high-frequency signal energy observed at the station. The events are listed in Table 1, and are shown on a map in Figure 1. In the following paragraphs, we discuss in some detail three of these events, which are quite typical in terms of the general characteristics observed for the waveforms. One is a presumed mining explosion in northern Sweden, and the other two are earthquakes south and north of Spitsbergen, respectively.

Mining event in Malmberget/Aitik, Sweden (Event 4—Distance about 330 km).

Figure 2 shows a spectrogram and waveform plot for a mining event in the Malmberget/Aitik area in northern Sweden. Malmberget is an underground iron ore mine, whereas Aitik is a nearby open-pit copper mine. The timing and size of the event are consistent with the explosion practice at Aitik, although we have not received confirmation from the mine authorities. We note a large amount of high-frequency energy for this event, up to the Nyquist frequency of 50 Hz. A particularly interesting observation is that the spectrogram shows distinct spectral lines, which is a characteristic feature for many ripple-fired explosions. It appears that the large bandwidth provided by the high-frequency recordings could be helpful in such cases to identify ripple-fired mining exposions.

Table 1. Events selected for analysis. Magnitudes are those of the International Data Centre (IDC) Reviewed Event Bulletin where available, otherwise the generalized beamforming (GBF) values automatically calculated at NORSAR are used.

No	Date	Origin time	Lat	Lon	Dkm	Region	Magnitude
1	2008/04/24	115-17:14:56.0	69.59	18.57	270.3	Troms, Norway	2.71 (GBF)
2	2008/04/12	103-23:17:05.0	67.77	20.41	285.2	Kiruna, Sweden	1.82 (GBF)
3	2008/04/12	103-23:19:21.0	67.77	20.41	285.2	Kiruna, Sweden	2.45 (GBF)
4	2008/04/01	092-17:08:10.0	67.03	21.09	333.5	Malmberget/Aitik, Sweden	2.12 (GBF)
5	2008/03/23	083-03:24:44.9	67.62	33.72	397.0	Kola Peninsula, Russia	2.53 (GBF)
6	2008/04/11	102-06:02:55.1	67.90	15.09	458.8	Steigen, Nordland, Norway	3.6 (IDC)
7	2008/04/10	101-06:20:00.1	77.02	18.59	863.0	Storfjorden, Svalbard	4.0 (IDC)
8	2008/04/07	098-23:51:14.2	76.38	7.24	961.4	Knipovich Ridge	4.1 (IDC)
9	2008/03/24	084-18:28:18.1	80.89	15.84	1292.5	North of Svalbard	3.8 (IDC)

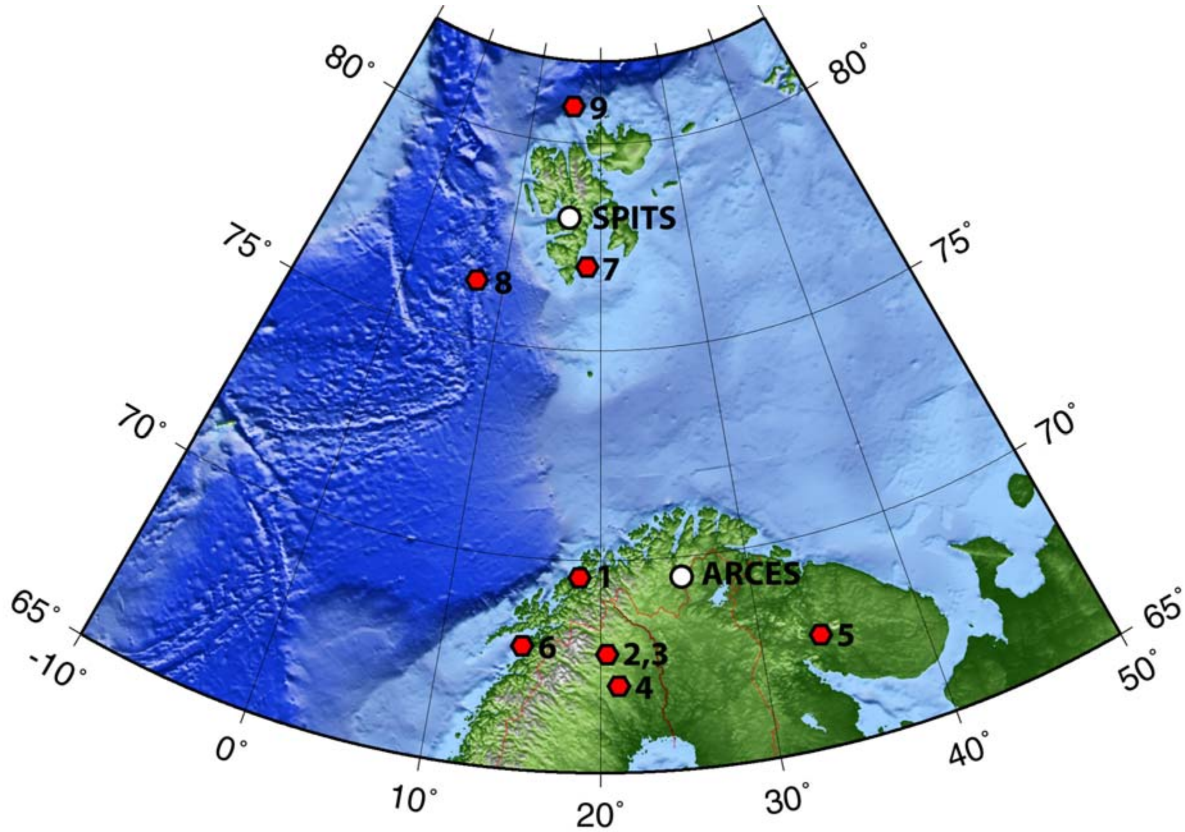

Figure 1. Map of the European Arctic showing the location of the seismic events analyzed in this study, together with the location of the ARCES and Spitsbergen arrays.

Earthquake Storfjorden, Spitsbergen (Event 7—Distance about 860 km).

This is an earthquake in a large aftershock sequence south of Spitsbergen. The main shock occurred on 21 February 2008 at 02.46.17 GMT. The magnitude of this earthquake was 6.2, making it the largest instrumentally recorded intraplate earthquake in Norway and surrounding areas. Figure 3 corresponds to one of the aftershocks occurring after the high-frequency system was installed at ARCES. The event magnitude is 4.0 as reported by the IDC. Like for the shorter epicentral distances, we note that there is significant signal energy even above 40 Hz. Again, the Pn and Sn phases are dominant. However, in the 1–2 Hz filter, there is a clear Lg phase about 1 minute after the Sn onset. This is surprising since the Barents Sea is generally considered as a region that has a distinct Lg blockage. This blockage is definitely seen for paths crossing the central Barents Sea (Baumgardt, 1990), but it appears from our observations that it is not quite so pronounced for paths covering the Western part of the Barents Sea. We have confirmed by vespagram analysis that this is indeed an Lg phase.

Earthquake north of Svalbard (Event 9—Distance about 1290 km).

This event, which is shown in Figure 4, is the event in our data set with the greatest epicentral distance (1,290 km) from the ARCES array. It is an intraplate earthquake, located on the continental slope north of Spitsbergen, with a travel path crossing the Svalbard archipelago as well as the western Barents Sea. Somewhat surprisingly, even this small earthquake (IDC magnitude 3.8) at such a large distance shows significant high-frequency signal energy in the 30-45 Hz band, especially for the Sn phase. This is clearly seen in Figure 4b and 4c. Furthermore, we again see evidence in Figure 4b of the Lg phase in the lowest frequency band (1–2 Hz).

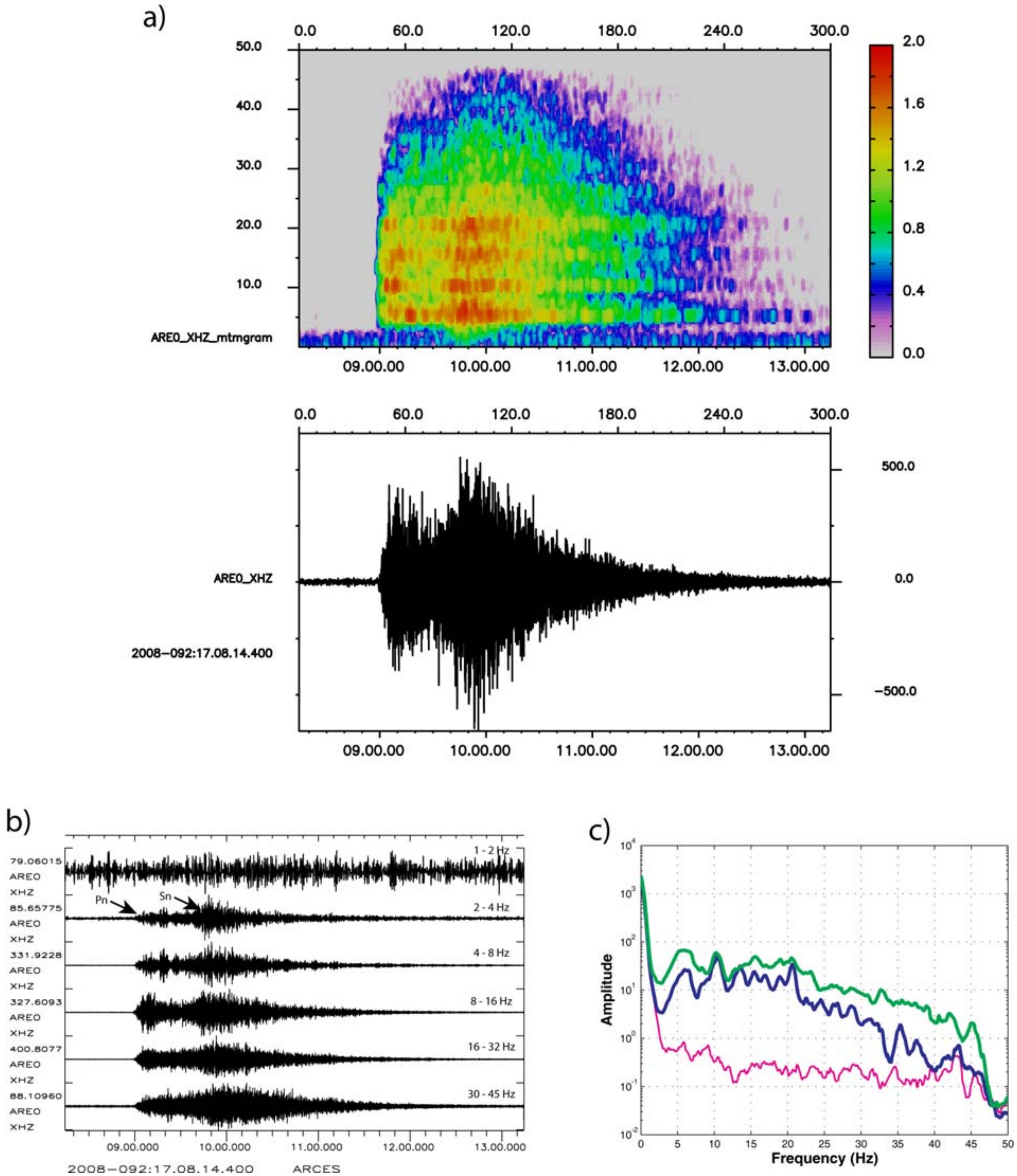

Figure 2. This figure shows various displays representing the vertical component of the ARCES high-frequency seismometer for Event 4 (Malmberget/Aitik, Sweden, at a distance of about 330 km): a) displays of 5 minutes of spectrogram and waveform plot filtered with a 2.2 Hz high-pass filter, b) waveform plot filtered in 6 different frequency bands, with the main regional phases indicated, c) amplitude spectra of noise and phases indicated in the waveform plot: noise (magenta), Pn (blue), Sn (green). See text for details.

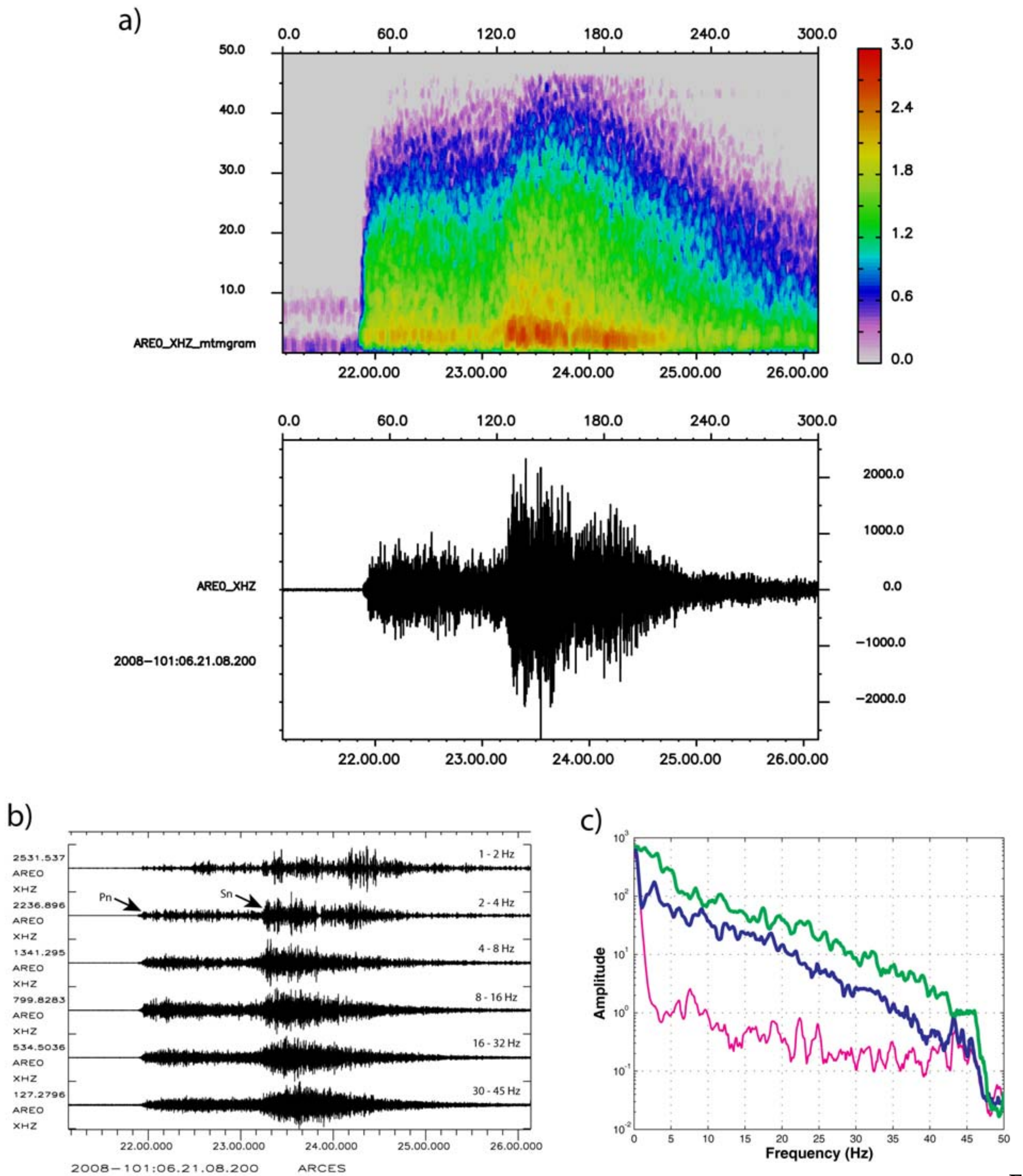

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Figure 3. This figure shows various displays representing the vertical component of the ARCES high-frequency seismometer for Event 7 (Storfjorden, Svalbard, Norway, at a distance of about 860 km): a) displays of 5 minutes of spectrogram and waveform plot filtered with a 2.2 Hz high-pass filter, b) waveform plot filtered in 6 different frequency bands, with the main regional phases indicated, c) amplitude spectra of noise and phases indicated in the waveform plot: noise (magenta), Pn (blue), Sn (green). See text for details.

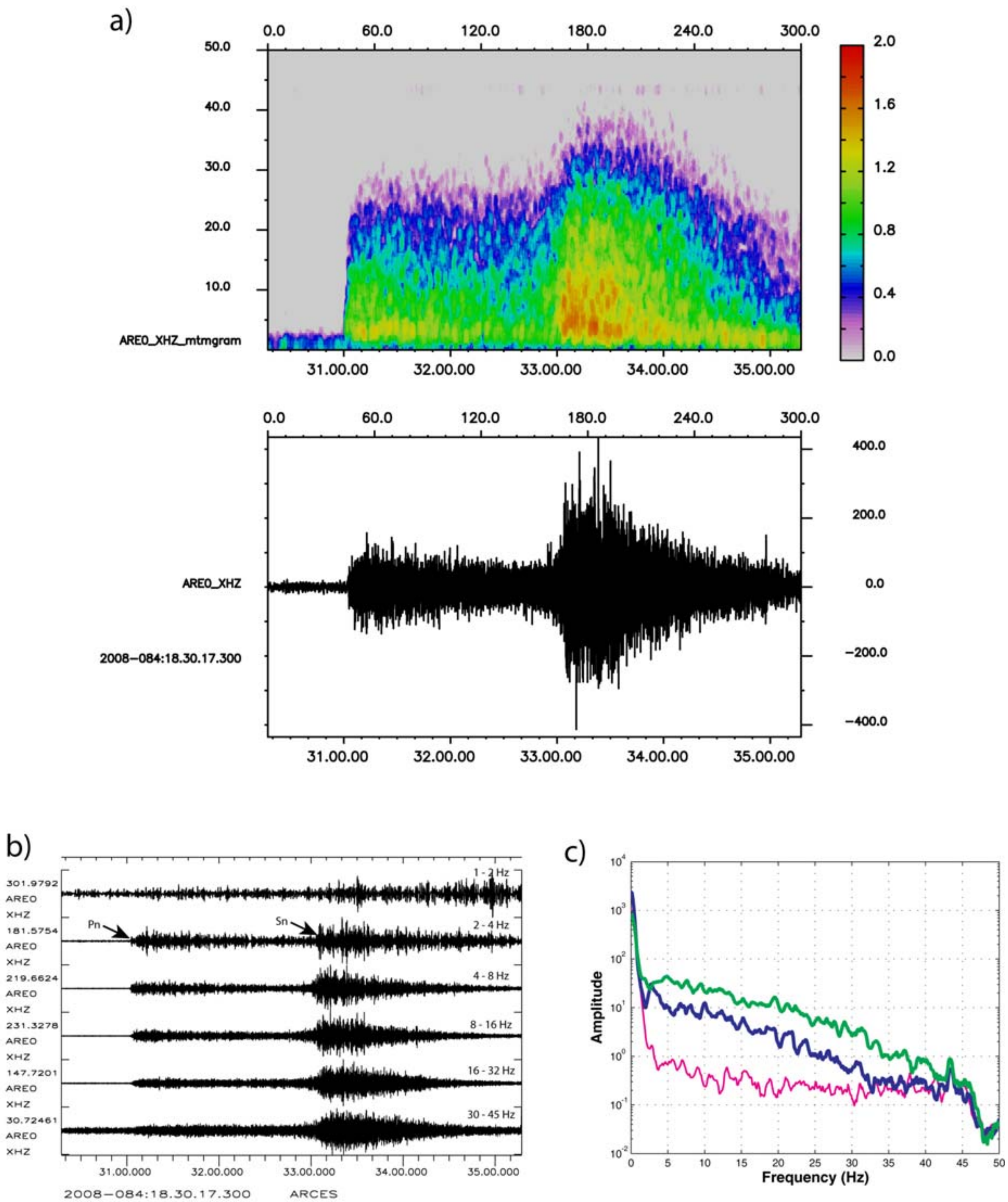

Figure 4. This figure shows various displays representing the vertical component of the ARCES high-frequency seismometer for Event 9 (north of Svalbard, at a distance of about 1,290 km): a) displays of 5 minutes of spectrogram and waveform plot filtered with a 2.2 Hz high-pass filter, b) waveform plot filtered in 6 different frequency bands, with the main regional phases indicated, c) amplitude spectra of noise and phases indicated in the waveform plot: noise (magenta), Pn (blue), Sn (green). See text for details.

We should note that the available high-frequency data so far do not include events to the east and northeast of the ARCES array, and the high-frequency propagation from the Novaya Zemlya region to ARCES is therefore still unknown. As more data are accumulated, we may be in a position to carry out a more detailed study of the propagation characteristics for additional paths in the region, and make a more systematic study of the benefits from combining the high-frequency observations from Spitsbergen and ARCES. Analysis of data from temporary seismic stations installed as part of a project under the ongoing International Polar Year is expected to provide an important contribution to such a study. This project is described by Schweitzer (2008) and involves the installation of 12 ocean-bottom seismometers, one new three-component broadband seismometer at Hornsund, Spitsbergen, one three-component broadband seismometer on the island of Hopen, and the installation of a small seismic array (13 three-component seismometers) on the Bear Island.

Infrasound Recordings of Rocket Launches from Plesetsk, Russia

The Plesetsk Cosmodrome is located about 800 km north of Moscow, with geographical coordinates 62.92 N 40.52 E. Plesetsk is used especially for military satellites placed into high inclination and polar orbits. However, global overviews on spaceflights, e.g., *http://en.wikipedia.org/wiki/2005_in_spaceflight*, show that geosynchronous satellites also are launched from this site. We have initially focused our attention on two launches, one on 19 June 2003 and another on 21 June 2005. See Table 2 for details.

Table 2. Rocket launches at the Plesetsk Cosmodrome Observed at the Infrasound stations in Apatity, Jämtön and Kiruna

Launch Year/Date/Time	Rocket	Orbit	Mission/Function
2003 19 June 20:00 GMT	Molniya M (R-7 8K78M)	Highly elliptical (Molniya)	Communications Satellite
2005 21 June 00:49 GMT	Molniya M	Geosynchronous	Communications Satellite

We have analyzed signals from these rocket launches recorded both at the Apatity infrasound array (Vinogradov and Ringdal, 2003) and by the stations of the Swedish Infrasound Network (Liszka, 2007). The Swedish network initially consisted of four infrasound stations: Kiruna, Jämtön, Lycksele, and Uppsala. The station in Uppsala was moved to Sodankylä, Finland, during the fall of 2006. Figure 5 shows the location of the infrasound stations currently in operation and the location of the Plesetsk Cosmodrome.

Data Processing

In order to get an overview of the signal characteristics, we have processed the infrasound data using vespagram analysis. Using a fixed apparent sound velocity of 0.333 km/s, we have calculated the resulting normalized beam power for a range of back-azimuths, where the maximum represents an estimate of the back-azimuth of the arriving signal. In our calculations we have used a window length of 10 seconds and a window step of 1.0 second. The Apatity infrasound data were processed in the 1–3 Hz frequency band, whereas the stations of the Swedish Infrasound network were all processed in the 2–5 Hz band. Figure 6 shows the results for the two Plesetsk rocket launches listed in Table 2 for the stations Apatity, Jämtön, and Kiruna. We observe the following general characteristics:

Apatity

- Some differences in waveforms between the 2003 and 2005 events.
- Quite similar azimuthal vespagrams, with a trend of changing back-azimuths versus time. Such observations are indicative of a moving source.
- Signal durations of almost 10 minutes. High signal-to-noise ratio (SNR) signals.
- Back-azimuths ranging between 145 and 137 degrees.

Jämtön:

- Quite similar waveforms and vespagrams for the 2003 and 2005 events.
- Signal duration of about 5 minutes. Moderate SNR signals.
- Back azimuths ranging between 91 and 102 degrees.

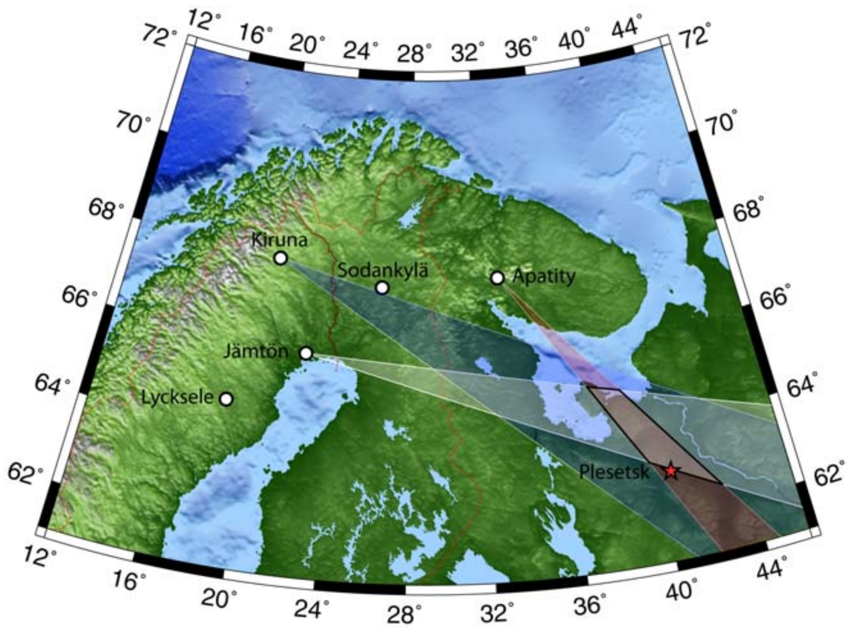

Figure 5. Map showing the location of existing infrasound stations in Sweden, Finland, and Northwest Russia (filled white circles). The location of the Plesetsk Cosmodrome is shown by the red star. The azimuthal sectors from Kiruna, Jämtön, and Apatity represent the range of back-azimuth estimates during the wavetrain of infrasound signals from the 2003 and 2005 rocket launches.

Kiruna:

- Quite similar waveforms and vespagrams for the 2003 and 2005 events.
- Signal duration of about 5 minutes. Low SNR signals with the influence of local noise.
- Back azimuths ranging between 101 and 118 degrees.

For two additional Plesetsk rocket launches in 2005 and 2007, we also have quite good recordings at the Apatity array. The 27 October 2005 signal is particularly interesting. It has characteristics similar to the 2003 and 2005 reference events, but with the exception that the trend of back-azimuthal change versus time is reversed. This may be explained by differences in rocket takeoff directions relative to the Apatity station.

In order to find how the direction estimates compare with the direction to the Plesetsk Cosmodrome, we have plotted azimuthal sectors from Apatity, Jämtön, and Kiruna spanning the range of azimuth estimates observed during the different infrasound wavetrains (Figure 5). It is interesting to note that the area of overlap between the different sectors includes the actual launch site. However, additional factors like atmospheric inhomogeneities, the wind field along the infrasound propagation path and the altitude and location of the infrasound source (the rocket) will most likely introduce biases in the azimuth estimates relative to the predicted Plesetsk direction.

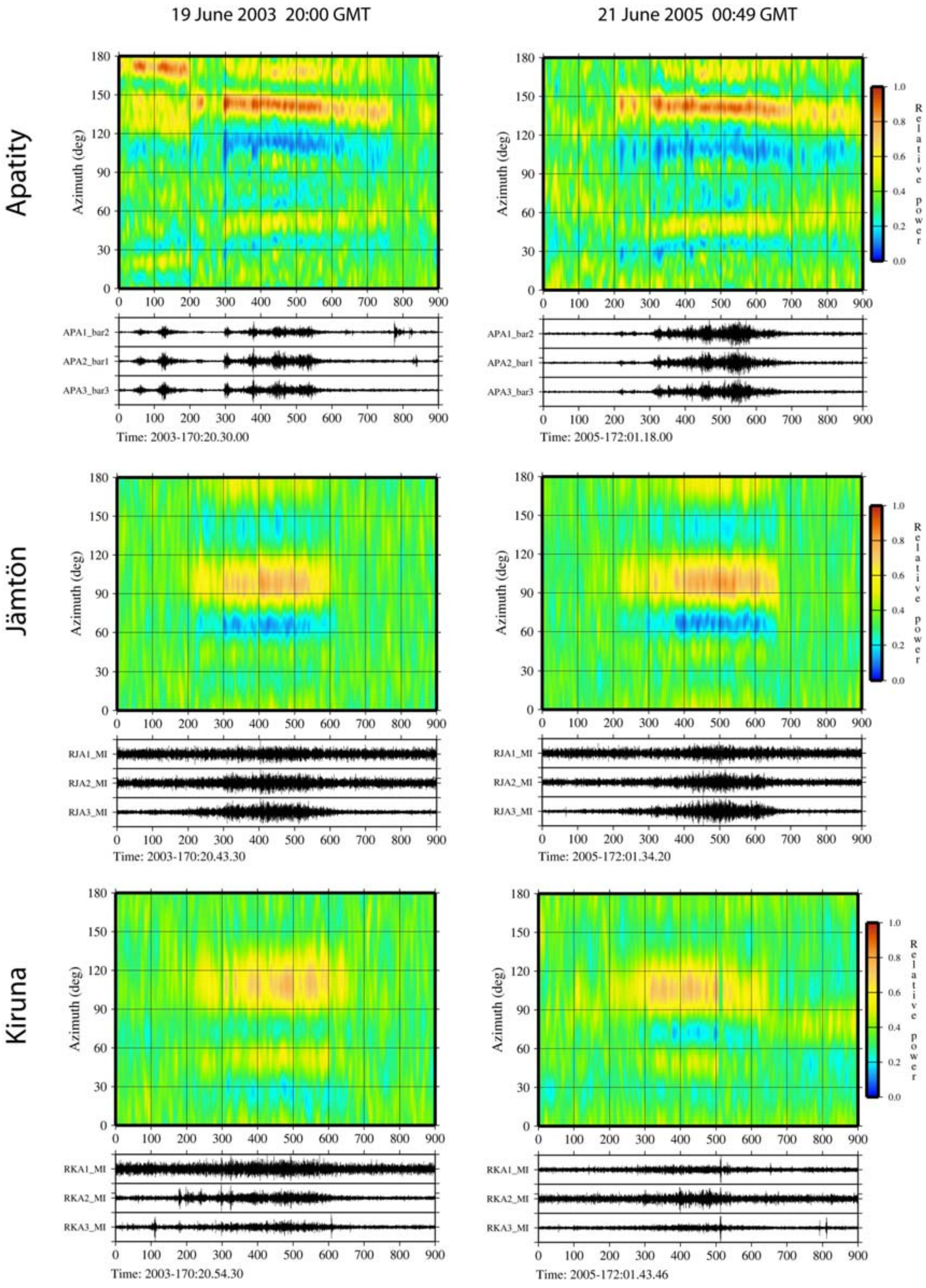

Figure 6. Each panel shows the infrasound waveforms from Apatity, Jämtön, and Kiruna as well as the corresponding azimuthal vespagram of the signals from the 2003 and 2005 Plesetsk rocket launches given in Table 2.

In addition to the confirmed rocket launches discussed above, we have also analyzed five unconfirmed events (which all occurred during one day—23 January 2007). For these events, we see signal characteristics that are

generally consistent with the observations of the confirmed launches, and it seems likely that they correspond to actual (unconfirmed) Plesetsk launches. We have calculated differential travel times for onsets of the infrasound signals at the Jämtön and Kiruna stations relative to Apatity. The onsets were read visually from vespagrams, and had a rather high uncertainty. We find that we cannot separate the source location for the unknown signals from the verified Plesetsk launches based on these differential travel times, and we therefore consider it likely that they could be rocket launches from this site.

CONCLUSIONS AND RECOMMENDATIONS

Previous studies (e.g., Ringdal et al., 2007) have shown a remarkably efficient seismic wave propagation from events near Novaya Zemlya across the Barents Sea to the Spitsbergen array. By analyzing data from a newly installed high-frequency element in the ARCES array in northern Norway, we have found that similar propagation characteristics are observed for this array as well. We note that the available high-frequency data so far does not include events to the east and northeast of the ARCES array, and the high-frequency propagation from the Novaya Zemlya region to ARCES is therefore still unknown. As more data are accumulated, we recommend that a detailed study of the high frequency propagation characteristics for various paths in the region be carried out. We also recommend that data from temporary seismic stations installed as part of the ongoing International Polar Year be fully exploited in such a study.

The Swedish infrasound array network provides a useful supplement to the seismic and infrasonic arrays in Norway and Northwest Russia. We have continued our infrasonic studies, applying the data from the available array network in northern Europe. As a special case study, we have analyzed recorded infrasound signals from four confirmed rocket launches at the Plesetsk Cosmodrome in northwest Russia as well as infrasound signals from five possible (unconfirmed) launches from the same site. The backazimuths estimated during the wavetrains show some significant variations, with a deviation from the theoretical values by up to about 10 degrees. The azimuthal pattern at the Apatity array shows a clear trend of changing backazimuths with time, thus giving indications of a moving source. We plan to continue these studies.

We continue our work towards developing and evaluating a joint seismic/infrasonic bulletin for northern Fennoscandia and adjacent regions. This bulletin would be similar to the automatic seismic bulletin that we are currently providing on the NORSAR Web pages, but it would also contain infrasonic phase associations. Furthermore, we will experimentally attempt to generate an infrasonic event bulletin using only the estimated azimuths and detection times of infrasound phases recorded by stations in the Nordic network.

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